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Advancing Holonic Systems in the Era of Artificial Intelligence and Digital Twins for Trustworthy and Effective Human-Centric Intelligent Systems

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Abstract

Holonic systems provide a powerful paradigm for modeling complex, distributed, and autonomous systems. However, their deployment in large-scale, heterogeneous environments raises challenges related to coordination, semantic alignment, bias migration, ethical reasoning, and real-time adaptation. This paper extends classical holonic architectures by introducing five complementary holon dimensions: effective, understanding, unbiased, vigilant, and ethical holons. Each dimension targets a specific capability required for resilient and socially responsible system behavior. These capabilities range from sustainability-aware decision-making and contextual understanding to bias mitigation and situation awareness. To enable coherent operation across autonomous and heterogeneous holons, this paper proposes to integrate federated interoperability as a foundational architectural principle. A dedicated federated interoperability holon (FIH) is proposed to dynamically manage technical and semantic interoperability. It also supports on-the-fly ontology alignment through short-lived ontologies as well as orchestrates coordination among specialized holons without centralized control. The framework is analyzed through a holon-based simulation approach, where holons act as autonomous simulation entities and are instantiated as High Level Architecture (HLA) federates. The applicability of the proposed framework is illustrated through a rural mobility use case focused on transportation systems. In this scenario, holonic coordination supports decision-making regarding multimodal integration, routing strategies, and the identification of mobility deserts. Overall, this work advances holonic system design by proposing an integration of specialized holon roles with federated interoperability mechanisms. It provides a scalable foundation for adaptive and socially aligned systems in domains such as mobility, smart territories, and enterprise ecosystems.

Keywords Holonic systems · Artificial intelligence · Digital twins · Holon-directed simulation · Federated interoperability · Rural mobility

1 Introduction

The concept of holons [26] provides a foundational abstraction for modeling complex systems composed of autonomous yet interdependent components. In the context of artificial intelligence (AI), digital twins (DT), and cyber-physical

systems (CPS), these technologies enable the creation of systems that are adaptable, resilient, and capable of autonomous decision-making [17]. Building on this foundation, holonic frameworks further enhance their ability to manage complex interactions.

Recent research has explored the application of holonic systems in various domains. For example, the MAS4AI framework [56] was introduced for human-centered, agile, and smart manufacturing, showing how holonic architectures integrated with artificial intelligence (AI) can enhance system performance. Another example is the Holon Programming Model [3] which was proposed as a software-defined approach to system-of-systems engineering that leverages holons for dynamic composition, collaboration, and adaptability.

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Additionally, the work by Irani et al. [21] on computationally aware systems recommended features through a review of 188 definitions, underscoring their relevance to advanced simulation. This research highlights the importance of computational awareness in the development of advanced holonic systems.

Furthermore, the study by Ören et al. [46] on an ontology-based dictionary of understanding provides a foundation for developing software agents with understanding capabilities. This ontology-based dictionary allows for a structured representation and processing of knowledge, which is essential for enabling context-aware interpretation and informed reasoning within holonic systems.

However, despite these advances, important limitations remain in current autonomous, adaptive, and holonic systems. In particular, existing approaches provide limited support for large-scale collaboration and adaptive coordination across heterogeneous systems without requiring structural modifications. These limitations reduce system responsiveness and robustness in dynamic, system-of-systems environments. To address these challenges, this paper extends the discussion on holonic systems by examining new conceptual dimensions pertaining to collaboration and federated interoperability, defined as the ability of two or more systems to communicate and operate together while adapting to environmental changes without requiring structural modifications. Specifically, we propose five complementary aspects that enhance decision-making quality, long-term effectiveness, contextual interpretation, fairness, and collective situational awareness within holonic systems. In addition, we investigate an extension of modeling and simulation paradigms toward holon-directed simulation, in which holons not only participate in simulations but also influence and direct simulation execution in response to evolving objectives and environmental conditions. Through this perspective, we explore synergies between systems engineering, simulation, computer understanding, awareness, and unbiasedness in the development of Human-Centric Intelligent Systems (HCIS).

To this end, we give a more extensive context regarding holonic systems as well as a more in-depth description of the motivation for this work in Sect. 2. Afterwards, we present a detailed description of holonic systems and simulations and identify some of the challenges currently affecting them in Sect. 3. We then describe the various proposed dimensions and ontologies for holonic systems in Sect. 4. Following that, the federated interoperability holon – made to facilitate orchestration, synchronization and collaboration – is introduced in the Federated Interoperability in Sect. 5. Subsequently, we present a rural mobility use case for a holonic system based on the newly proposed holon and HLA-based simulation in Sect. 6. Finally, we present future work possibilities and conclude this work in Sect. 7.

2 Background and Motivation

2.1 Holons and Holarchy

Holons and agents share several similarities, and it is therefore necessary to highlight their differences. According to Ören [39, 41], holons are self-contained entities that function simultaneously as autonomous wholes and as dependent parts of a larger system, organized according to the principles of holarchy – an organizational structure in which holons are recursively nested across multiple levels. Each holon retains local autonomy while contributing to the objectives of higher-level holons, typically called superholons, whereas holons contained within them are referred to as subholons, as shown in Fig. 1. While similar to agents in their autonomous behavior, holons authority, decision-making and scope of application are constrained by their position in the hierarchy, forming a pyramid-like structure. In this hierarchy, top-level holons possess the greatest authority, while lower-level holons execute directives from higher levels within the bounds of their local autonomy, aligning decisions with overarching system objectives [5].

Unlike rigid, centralized hierarchies, a holarchy distributes authority, responsibility, and decision-making across levels, preserving local autonomy and adaptability. This structure enables coordination, scalability, and resilience, allowing global system behavior to emerge from locally autonomous but structurally constrained components. A holonic system is a practical instantiation of this principle – a system composed of interacting holons that perform tasks, make decisions, and collaborate according to the holarchy.

In contrast, agents in multi-agent systems (MAS) are autonomous entities that interact with others to achieve individual or collective goals, operating in decentralized and non-hierarchical environments. In the DT systems, there is

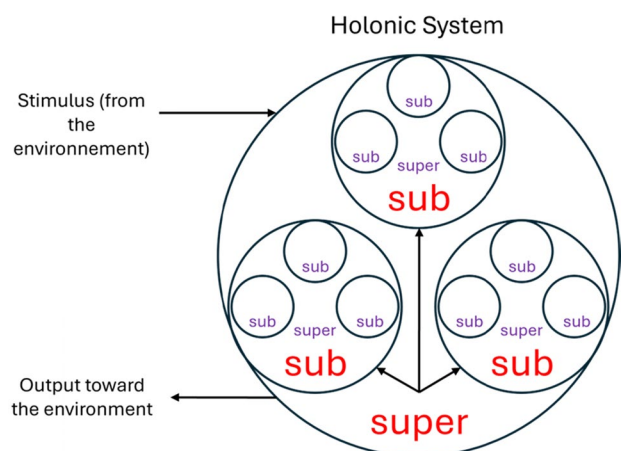


Fig. 1 Holonic System Structure

an interest in using the holarchy approach to define some orchestrator holons that deal with interoperability between holons while driving domain specific agents (sub hierarchical level holons). Additionally, keeping humans in the loop leads to a hybrid approach that mixes human-artificial agents in the system. In between agents, Agentic AI [49] can offer more flexibility in collaboration.

Holonic systems have been applied in various domains, including manufacturing, supply chain management, and healthcare. For example, in manufacturing, holons can optimize production processes by dynamically reallocating resources, while in healthcare, holons can analyze patient data to recommend personalized treatment plans. However, the integration of AI and digital twins has opened new avenues for holonic systems to evolve. DT provides real-time data and virtual representations of physical systems, enhancing the autonomy and adaptability of holonic systems.

2.2 Historical Context and Evolution of Holonic Systems

The concept of holons has its roots in the work of Koestler [26], who introduced the idea of entities operating simultaneously at multiple levels of organization. Building on his philosophical foundations, researchers in the manufacturing domain recognized the potential of holonic principles for engineering complex, adaptive production systems. In the early 1990s, the Holonic Manufacturing Systems (HMS) [61] paradigm was developed within the Intelligent Manufacturing Systems (IMS) research initiative to address limitations of traditional manufacturing architectures, such as centralized control and poor adaptability to change. The HMS concept models manufacturing resources – including machines, cells, products, and operators – as autonomous, cooperative holons that can self-organize and negotiate to achieve production goals in a flexible and distributed manner [4, 16].

One early scientific conceptualization of this paradigm is the work on holonic manufacturing scheduling which formalized how holons—defined as entities with both informational and physical components—cooperate within a holarchy to coordinate activity and make decentralized decisions to meet manufacturing objectives in dynamic environments [18]. Subsequent research has elaborated on mechanisms for holarchy formation and optimization, demonstrating how holons can dynamically reconfigure coordination structures to respond to changes in production requirements and disturbances in the system [20].

Over time, the application of holonic concepts expanded beyond manufacturing into broader socio-technical systems. Recent studies highlight the translation of holonic structures into contexts such as multi-agent systems, cyber-physical production systems, and sustainable organizational

architectures, reflecting the general utility of holonic principles for managing complexity, autonomy, and cooperation in diverse domains [4].

2.3 Recent Advances in Holonic Systems

Recent advancements in holonic systems research continue to expand both the theoretical foundations and practical applications of holonic architectures across diverse domains. Beyond the early application of holonic principles in manufacturing, contemporary research demonstrates how holonic concepts are being integrated with advanced computational frameworks, decision-making methods, and digital infrastructure to support complex, dynamic systems.

For instance, the design of holonic smart grid architectures illustrates how decentralized, holon-based control can enhance resilience and adaptive operation in power and energy systems, enabling intelligent coordination among distributed energy systems, enabling intelligent coordination among distributed energy resources and responding robustly to disturbances in real time [50]. Similarly, research has proposed holonic multi-agent structures for decision-making in smart grids, combining genetic algorithms and decentralized control strategies to improve system resilience and optimize performance under uncertainty [57]. These studies show how holonic systems can move beyond traditional manufacturing contexts to address critical challenges in infrastructure, energy, and resource management.

Recent work also explores extending holonic architectures into cyber-physical holon designs, where holons are mapped to both physical and virtual components using multi-agent system principles, facilitating continuous intelligent decision-making and self-organization in cognitive manufacturing and other complex systems [32]. Studies on holonic reengineering for sustainable cyber-physical systems demonstrate that integrating holonic principles with CPS and intelligent agents supports adaptive autonomy and resilience, positioning holons as active elements within Industry 4.0 and beyond [32].

Furthermore, the holonic paradigm continues to be applied in real-time complex project execution domains, such as construction management, where holonic execution systems support dynamic scheduling and resource coordination linked to building information models (BIM), demonstrating adaptability and robustness in non-manufacturing contexts [35]. Other research in data collection and processing methodologies for holonic systems provides experimental insights into how communication interfaces and intelligent data pipelines can support real-time holon interaction and performance optimization in industrial environments [34].

These recent advances underscore the evolution of holonic systems from their origins in flexible manufacturing

toward broader, cross-domain frameworks capable of operating within smart infrastructure, CPS, energy-critical domains, and intelligent multi-agent networks. This evolution reflects not only the increasing complexity of engineered systems but also the growing need for adaptive, resilient, and autonomous coordination mechanisms that holonic architectures are well positioned to provide.

2.4 Challenges and Limitations of Current Autonomous Systems

Despite the substantial advances in artificial intelligence, digital twins, and autonomous decision-making technologies, current autonomous systems continue to face several persistent challenges and limitations. A key limitation concerns their restricted adaptability in dynamic and uncertain environments. Many autonomous systems rely on predefined models, assumptions, or learned policies that do not generalize well when operating conditions change unexpectedly, leading to degraded performance or unsafe behavior in complex real-world settings [28]. This issue is particularly pronounced in large-scale and System-of-Systems contexts, where heterogeneous components must dynamically interact, reconfigure, and maintain interoperability at runtime [9, 37].

Another critical challenge is the presence of cognitive and algorithmic biases in autonomous decision-making processes. These biases may originate from training data, model design choices, or implicit assumptions embedded within learning algorithms, and can result in unfair or discriminatory outcomes. Such risks are especially concerning in socially sensitive domains such as finance, healthcare, and public services, where autonomous decisions may significantly affect individuals or groups [22, 63].

In addition, ethical and responsibility-related concerns remain insufficiently addressed in many autonomous systems. As these systems increasingly make or support decisions with moral, legal, and societal implications, questions of accountability, responsibility attribution, and compliance with ethical principles become critical. Existing approaches often lack explicit mechanisms for reasoning about responsibility, blame, or ethical trade-offs, limiting trust and acceptance of autonomous technologies [22, 63].

Finally, many autonomous systems exhibit limited situational awareness and contextual understanding, constraining their ability to interpret complex environments, integrate heterogeneous information sources, and collaborate effectively with humans, or other autonomous entities. Insufficient transparency, explainability, and shared awareness can hinder human-AI cooperative interactions and reduce overall system effectiveness, particularly in safety-critical and time-sensitive applications [14, 31].

2.5 Motivation for Integrating Holonic Principles

Integrating holonic principles with autonomous systems such as artificial intelligence and digital twins offers a promising solution to address several limitations in current autonomous and adaptive technologies. AI-enhanced digital twins have evolved from static models into autonomous, adaptive, and resilient cyber-physical systems capable of real-time monitoring, predictive analytics, and proactive decision-making, which aligns with holonic goals of decentralized awareness and responsiveness [36, 60]. By embedding such capabilities into holonic structures, individual holons can leverage continuous data flows and AI insights to make more informed decisions, improving flexibility and system-wide robustness in dynamic environments while preserving local autonomy.

Furthermore, emerging work in smart manufacturing illustrates how federated learning and edge AI integrated with digital twins can support real-time co-simulation and adaptive learning across distributed components, reducing the need for centralized data aggregation and enhancing scalability and privacy—attributes desirable in holonic ecosystems with distributed decision-making units [2]. This combination of AI, federated learning, and digital twin technologies suggests a pathway toward self-optimizing and collaborative holonic systems that can adjust to changing conditions and unanticipated scenarios without requiring global reconfiguration.

Holonic systems extended with AI also create opportunities for greater resilience and fault tolerance. Incorporating predictive models and adaptive control enables dynamic reconfiguration of roles and behaviors among holons, helping the system respond to disturbances and sustain performance without centralized oversight. Research on digital twin and AI integration consistently highlights how data-driven insights, reinforcement learning, and scenario analysis contribute to autonomous optimization and resilience in complex environments [36, 60].

Moreover, the incorporation of ethical guidelines and unbiased decision-making processes within holonic systems is critical for ensuring fair and transparent outcomes as autonomous decision-making expands. Ethical AI frameworks emphasize the importance of embedding principles such as fairness, accountability, and transparency directly into system design to mitigate bias and unintended negative consequences, an important requirement when decision authority is distributed among autonomous holons [33, 51]. For instance, holons responsible for ethical considerations, which are detailed further in Sect. 4.1, can be designed to prioritize safety, fairness, and public trust in contexts where decisions have tangible impacts on people's lives. Research in AI ethics and decision-making highlights how structured ethical frameworks and bias mitigation strategies help

autonomous systems align with societal values and reduce discriminatory outcomes, supporting this holonic extension [33].

Collectively, these developments motivate the integration of holonic principles with AI and digital twin technologies. By combining decentralized autonomy, real-time data integration, federated learning, and ethical decision support, holonic systems may potentially overcome current limitations in adaptability, transparency, and bias mitigation. This integration paves the way for smarter, more resilient, and ethically aligned autonomous systems that operate effectively in complex, evolving environments.

3 Holon-Directed Systems and Simulation

Agent-directed simulation (ADS), part of the Modeling & Simulation (M&S) paradigm [44], is based on the synergy of software agents and simulation, and its aspects have been extensively detailed in several foundational works [45, 64]. ADS provides a very rich paradigm encompassing both the use of simulation to model agents (agent simulation or agent-based simulation) and the use of agents to support simulation (agent-supported simulation and agent-monitored simulation) [64]:

1. *Agent simulation* or *agent-based simulation* is the simulation of systems modeled by agents and is a very powerful and widely used paradigm [54]. This is due to the fact that it can benefit from all types of software agents, including intelligent and autonomous agents. It can also benefit from all types of simulation and its applications such as experimentation [42] and experience gain, which serve to either enhance three types of skills [43] or for entertainment [53]. These three types of skills are motor skills, decision-making and communication skills, and operational skills. Motor skills are developed through virtual simulation, wherein real individuals operate virtual equipment within virtual environments. Decision-making and communication skills are enhanced through constructive simulation; wherein real individuals interact with a simulation system involving simulated people and simulated equipment. Finally, operational skills are improved through live simulation, wherein real individuals use virtual or dummy equipment in real-world settings [43].
2. *Agent-supported simulation* uses intelligent agents to enhance simulations by providing cognitive assistance in problem specification and solving. These agents improve simulation infrastructures by offering computer assistance for interface functions, ensuring consistency and reliability, as well as adding cognitive abilities such as learning and understanding [54].
3. *Agent-monitored simulation* uses agent technologies to monitor and generate model behavior. Intelligent agents can act as simulation coordinators, making run-time decisions for dynamic model composition and adaptation. Their perceptive and deliberative capabilities make them essential for complex experiments, knowledge processing, and enhancing the composability and interoperability of simulation models and software systems [54].

These concepts, originally defined for agent-directed simulation, are also applicable to holon-directed simulation, given the shared autonomous, goal-oriented, and reactive characteristics of agents and holons. Moreover, both simulation paradigms have been extensively catalogued in the M&S literature, providing guidance on methodologies, implementation considerations, and federated environments [45]. The intellectual foundations of ADS are rooted in several seminal works [38, 41, 64].

Agents, in this context, are autonomous, goal-oriented entities capable of perception, reasoning, and action. Their behaviors and interactions can lead to complex patterns at the system level. For example, Schelling [55] demonstrated how simple individual preferences can give rise to large-scale patterns of social segregation in the absence of centralized control. These realizations led to one of the earliest agent-based models, a modeling paradigm that continues to evolve through multiple research communities such as Agent-Based Models [1]. Similarly, Epstein and Axtell [15] showed in their artificial societies how local interactions among agents can generate complex societal dynamics. These works illustrate how agents, through decentralized interactions, can give rise to emergent patterns – insights that provide important background for understanding the behavior and design of agents in ADS, and, subsequently, of holons in holon-directed simulation.

Subsequently, agents are central to ADS, particularly in modeling complex adaptive systems where individual behaviors and interactions give rise to system-level phenomena. Drawing on this, the concept of holons adds a new dimension. Building on the distinction introduced in Sect. 2, holons extend traditional notions of agent-based approach notions by introducing hierarchical and recursive organizational constraints that enable multi-level coordination and control.

This leads to the notion of holonic agents – agents endowed with a holonic structure. These agents retain the autonomy of traditional agents but also exhibit organizational awareness and the ability to coordinate across multiple levels [39]. Such capabilities make them especially well-suited for simulating complex, distributed, and hierarchical systems, including manufacturing networks, military command structures, and biological systems.

Ören [39, 40] posits that holonic-agent simulation represents a natural evolution of agent-based simulation, offering enhanced scalability, modularity, and resilience. Extending this trajectory, we introduce the concept of holon-directed simulation—a novel approach in which holons, as autonomous and cooperative entities, not only participate in simulations but also dynamically direct the simulation process in response to evolving objectives and environmental conditions. This marks the first formal use of the term *holon-directed simulation*, signifying a significant step forward in the evolution of holonic modeling and simulation paradigms.

3.1 Types of Holon-Directed Simulation

Based on various work on agent-directed simulation and given that holons are a special class of agents, we can infer a categorization for holon-directed simulation types from classification of agent-directed simulation approaches. Hence, we have holon simulation (or holon-based simulation), holon-supported simulation, and holon-monitored simulation. Holon-directed simulation can further be categorized into several types, depending on the level of autonomy and the decision-making capabilities of the holons within the system:

- **Passive Holon-Directed Simulation:** Holons act primarily as data sources and do not directly alter the simulation process. They provide insights and feedback but do not make autonomous decisions about simulation execution [11].
- **Reactive Holon-Directed Simulation:** Holons respond to changes in the simulation in real time, adjusting parameters dynamically based on environmental conditions or new data inputs [23, 27].
- **Adaptive Holon-Directed Simulation:** Holons not only react to changes but learn from past simulations to optimize decision-making and resource allocation over time [48].
- **Proactive Holon-Directed Simulation:** Holons actively modify simulation rules, introduce new objectives, and collaborate across different federated systems to influence long-term outcomes [23].

3.2 Implementation Considerations

Implementing holon-directed simulation [45] requires advanced algorithms that enable holons to:

- Analyze real-time simulation data and adapt their roles dynamically.
- Coordinate with other holons to achieve global system optimization.

- Integrate federated interoperability to operate across distributed environments (e.g., smart manufacturing, autonomous logistics, and resilient supply chains).

For example, in a manufacturing simulation, holon-directed systems can autonomously reallocate resources, adjust workflows, and optimize scheduling based on real-time feedback from digital twins. This results in enhanced efficiency, reduced downtime, and improved adaptability.

3.3 Challenges

Despite its potential, holon-directed simulation presents several challenges:

- **Computational complexity:** Managing autonomous holons in real-time simulations requires significant processing power and efficient algorithms.
- **Standardization:** Establishing universal protocols for holon-directed systems is essential for cross-domain applications.
- **Integration with AI and Digital Twins:** Future research must explore how machine learning and digital twin technologies can enhance the decision-making capabilities of holons within simulations.

By integrating holon-directed simulation into various domains, we can develop self-adaptive, federated, and resilient systems that revolutionize industries such as manufacturing, healthcare, and transportation.

4 Proposed Dimensions of Holonic Systems

We propose several new dimensions of holonic systems that address certain limitations of current autonomous and adaptive systems discussed in Sect. 2.4, and introduce a structured conceptual framework for more intelligent, ethical, and human-centric systems. While holons are not necessarily fully autonomous, they possess local decision-making capabilities whose degree of autonomy may vary depending on hierarchical constraints, coordination mechanisms, and system objectives. By leveraging the organization properties of holonic systems, the proposed dimensions in the subsequent Sects. 4.1, 4.2, 4.3, 4.4 and 4.5—ethical holons, effective holons, understanding holons, unbiased holons, and vigilant holons – provide a structured conceptual framework for mitigating certain shortcomings of existing autonomous systems. Autonomous systems adopting these dimensions are thus ultimately framed and realized as holonic systems, in which holons encapsulate and coordinate the proposed capabilities.

4.1 Ethical Holons

Autonomous systems often operate in situations that require moral or legal decision-making, and without guidance, they may act in a manner that is harmful, unfair, or socially unacceptable [22, 63]. Within holonic systems, we propose introducing ethical holons as a new dimension capable of addressing this problem by operating within a framework of ethical guidelines. They can distinguish right from wrong and cooperate with other holons to achieve ethical outcomes, rather than forming opportunistic or self-interested coalitions and acting unethically while trying to respond to a request.

4.1.1 Implementation Methodology and Examples

Ethical holons can be implemented through a combination of ontology-based ethical representations, normative rule systems, and constraint-based decision-making mechanisms. Ethical principles such as safety, legality, responsibility, and harm minimization can be formally encoded using ethical ontologies and semantic models, allowing ethical constraints to be explicitly evaluated alongside operational objectives. Ontology-based requirements engineering has been demonstrated as a method to capture ethical requirements and translate them into system design artifacts that guide behavior in autonomous systems, supporting structured ethical decision-making during development and runtime operations [19].

By embedding ethical guidelines through such mechanisms, ethical holons can operationalize moral reasoning directly within holonic decision processes, enabling their application in safety-critical and value-critical domains such as:

- **Autonomous Vehicles:** they can prioritize pedestrian safety, legal compliance, and harm minimization over efficiency-based objectives such as minimizing travel time. Similar normative and ontology-based approaches have been studied to regulate ethical decision-making in autonomous agents and vehicles.
- **Healthcare Systems:** they can guide resource allocation decisions based on ethical priorities such as urgency and fairness, particularly in constrained environments such as pandemics.

4.1.2 Challenges

The main implementation challenges lie in:

- **Defining Ethical Guidelines:** one of the main challenges in implementing ethical holons is defining the ethical guidelines they should follow. These guidelines must be comprehensive and adaptable to different contexts.
- **Balancing Ethics and Efficiency:** ethical holons must balance ethical considerations with the need for efficiency. This requires sophisticated decision-making algorithms that can weigh different factors and make optimal decisions [22, 63].

4.2 Effective Holons vs. Efficient Holons

Many autonomous systems focus solely on efficiency, achieving goals rapidly but potentially overlooking long-term impacts or broader societal benefits [28]. Within holonic systems, we propose incorporating effective holons as a new dimension capable of addressing this limitation by achieving objectives in a manner that is not only efficient but also effective, considering broader consequences, sustainability, and long-term outcomes. In contrast, efficient holons focus solely on achieving their goals with minimal resource usage, without accounting for wider or long-term effects.

4.2.1 Implementation Methodology and Examples

Effective holons extend efficiency-oriented optimization by integrating multi-criteria decision-making, long-term utility modeling, and sustainability-aware evaluation metrics. Unlike efficient holons, which optimize short-term resource usage, effective holons can employ decision models that consider broader consequences, including environmental impact, social responsibility, and long-term system performance. Techniques such as weighted utility functions, goal hierarchies, or policy-based optimization can be used to balance short-term efficiency against long-term effectiveness [59].

Through the use of multi-criteria decision-making models, long-term utility evaluation, and sustainability-aware performance metrics, effective holons extend beyond short-term efficiency optimization, enabling their application in domains such as:

- **Autonomous Vehicles:** they can prioritize pedestrian safety, legal compliance, and harm minimization over efficiency-based objectives such as minimizing travel time. Similar normative and ontology-based approaches have been studied to regulate ethical decision-making in autonomous agents and vehicles.
- **Healthcare Systems:** they can guide resource allocation decisions based on ethical priorities such as urgency and fairness, particularly in constrained environments such as pandemics.

4.2.2 Challenges

The main implementation challenges lie in:

- **Measuring Effectiveness:** measuring effectiveness can be challenging, as it involves considering long-term impacts and broader societal benefits. This requires the development of new metrics and evaluation methods. Regression models that result in scores depending on the issue and the metric; could also be a majority vote model. The previous two could even include rule-based criteria depending on the situation or domain.
- **Balancing Short-Term and Long-Term Goals:** effective holons must balance short-term efficiency with long-term effectiveness. This requires sophisticated planning and decision-making capabilities.

4.3 Understanding Holons

Autonomous systems operating in complex environments often struggle to interpret context, integrate heterogeneous information, and reason about situations in a meaningful way, which limits their ability to make informed decisions [31, 37]. Inspired by Ören et al.'s work [46], we propose introducing understanding holons as a new dimension that allows holons to comprehend complex situations through structured knowledge representation, such as ontology-based dictionaries of understanding, enabling informed and context-aware decision-making.

4.3.1 Implementation Methodology and Examples

Understanding holons can be implemented using ontology-based knowledge representation, semantic reasoning, and context-aware data fusion. Domain ontologies provide structured representations of entities, relationships, and processes, enabling holons to interpret heterogeneous data consistently. Semantic reasoning mechanisms allow inference of higher-level situational knowledge from incomplete or noisy inputs. These holons may also incorporate machine learning models to enrich symbolic representations with learned patterns [62].

By leveraging ontology-based knowledge representation, semantic reasoning, and context-aware data integration, understanding holons can transform heterogeneous and dynamic data into meaningful situational knowledge, supporting informed decision-making in domains such as:

- **Healthcare:** they could analyze patient data and recommend personalized treatment plans based on a deep understanding of medical ontologies. For example, an

understanding holon could identify patterns in patient data that indicate a high risk of a particular disease and recommend preventive measures.

- **Disaster Response:** they could analyze data from various sources, such as weather reports and social media, to provide real-time situational awareness and recommend appropriate actions.

4.3.2 Challenges

The main implementation challenges lie in:

- **Developing Ontologies:** developing comprehensive and accurate ontologies is a significant challenge. These ontologies must be able to represent complex knowledge domains and be adaptable to new information.
- **Processing Large Volumes of Data:** understanding holons must be able to process large volumes of data in real-time. This requires advanced data processing and machine learning capabilities.

4.4 Unbiased Holons

Decision-making processes in autonomous systems may unintentionally embed cognitive or data-driven biases, leading to unfair or discriminatory outcomes, especially in socially sensitive domains [22, 63]. Within holonic systems, we propose incorporating unbiased holons as a new dimension aimed at minimizing such biases by enabling holons to identify, reason about, and mitigate cognitive biases, for instance through ontology-based representations of known bias patterns. Holons lacking this dimension may unknowingly propagate biased decisions despite operating efficiently.

4.4.1 Implementation Methodology and Examples

Unbiased holons can be implemented through bias-aware knowledge models, fairness constraints, and monitoring mechanisms that identify and mitigate cognitive or data-driven biases. Ontologies of known bias patterns can be used to explicitly represent sources of bias, while fairness-aware decision models and post-decision auditing mechanisms help detect and correct biased outcomes. These mechanisms can be integrated into holonic decision loops to ensure continuous bias assessment [47].

By incorporating bias-aware knowledge models, fairness constraints, and continuous monitoring mechanisms into holonic decision processes, unbiased holons enable fairer and more transparent decision-making in socially sensitive applications such as:

- **Financial Systems:** they could ensure fair and transparent decision-making, reducing the risk of discriminatory practices. For example, an unbiased holon could analyze loan applications without being influenced by biases related to the applicant's gender, race, or socioeconomic status.
- **Hiring Processes:** they could ensure that candidates are evaluated based on their qualifications and skills, rather than being influenced by biases related to their background or appearance.

4.4.2 Challenges

The main implementation challenges lie in:

- **Identifying Biases:** identifying and understanding cognitive biases is a complex task. This requires extensive research and the development of comprehensive bias ontologies.
- **Mitigating Biases:** mitigating biases in real-time decision-making processes is challenging. This requires sophisticated algorithms that can detect and correct biases as they occur. Similar research has been done on identifications, with one example being defects and faults in systems. Hence, similar models and techniques could be used here.

4.5 Vigilant Holons and Holons with Awareness

As systems increasingly operate as part of larger collectives, a lack of shared awareness can limit cooperation and reduce overall system performance [14, 31]. Within holonic systems, we propose introducing vigilant holons as a new dimension that emphasizes shared situational, task-related, and social awareness across holons, facilitating coordination and collective decision-making. Without this dimension, holons may remain locally informed but globally misaligned, reducing the effectiveness of the holonic system as a whole.

4.5.1 Implementation Methodology and Examples

Vigilant holons emphasize situational awareness, shared context modeling, and coordination mechanisms across holons. They are implemented using distributed sensing, real-time data aggregation, and awareness models that represent system-wide states, goals, and social contexts. Communication protocols and coordination frameworks enable vigilant holons to disseminate relevant awareness information across hierarchical levels [31].

Through distributed sensing, shared situational awareness models, and coordination mechanisms across hierarchical levels, vigilant holons support collective awareness

and alignment, enabling effective coordination in large-scale domains such as:

- **Disaster Response:** they could monitor environmental conditions and coordinate rescue efforts in real-time. For example, a vigilant holon could detect a natural disaster, such as an earthquake, and coordinate the deployment of emergency services to affected areas.
- **Smart Cities:** they could monitor traffic conditions, energy usage, and public safety. For example, a vigilant holon could detect a traffic accident and reroute traffic to prevent congestion and ensure that emergency services can reach the scene quickly.

4.5.2 Challenges

The main implementation challenges lie in:

- **Developing Awareness Capabilities:** developing the various types of awareness required for vigilant holons is a complex task. This requires advanced sensing, data processing, and machine learning capabilities.
- **Ensuring Collaboration:** ensuring effective collaboration between vigilant holons and other entities is challenging. This requires the development of standardized communication protocols and collaboration frameworks.

4.6 Holonic Dimensions Relationships

To emphasize the recursive and interconnected nature of holons, and their distinction from standalone agents, we extend the previous mapping to show how holons relate to each other. Each holon contributes specialized capabilities while maintaining local autonomy.

For instance:

- **Ethical and unbiased holons** provide complementary checks on decisions to ensure fairness, safety, and compliance. They feed their evaluations to effective holons, which balance operational efficiency with long-term objectives.
- **Understanding holons** interpret heterogeneous data and contextual cues, supporting both effective and unbiased holons by providing situational knowledge that informs fair and efficient decision-making.
- **Vigilant holons** operate across all layers, monitoring outputs of subordinate holons and system-wide states, ensuring that local decisions are globally aligned.

This recursive interaction allows holons to retain their local autonomy while functioning as parts of larger, goal-aligned holarchies, thereby operationalizing both their specialized and collective capabilities. Table 1 illustrates these

Table 1 Mapping of proposed holonic dimensions to sub-objectives, interaction roles, and recursive relations within the holonic hierarchy

Issue	ETH	EFH	USH	UBH	VIH	Notes on interaction and recursive relation
Norm compliance in local decisions	✓	✗	●	●	✗	Ethical holons enforce norms at the leaf-holon level; they may be nested within higher-level holons that aggregate ethical constraints across subsystems
Ethical conflict resolution	✓	●	✓	●	●	Conflicts are resolved locally by ethical holons, with vigilant holons escalating unresolved conflicts to a superholon when multiple sub-holons are involved
Long-term outcome evaluation	●	✓	●	✗	●	Effective holons evaluate long-term impact locally; aggregated evaluations may inform higher-level planning holons
Contextual interpretation	✗	✗	✓	●	✗	Understanding holons operate at multiple hierarchical levels, each interpreting context relevant to its scope
Contextual alignment across holons	✗	✗	●	✗	✓	Vigilant holons reconcile context interpretations across sibling holons, enabling coherent behavior at the superholon level
Bias detection in local decisions	✗	✗	●	✓	✗	Unbiased holons monitor and correct bias locally; results are encapsulated and reported upward if systemic patterns emerge
Systemic bias monitoring	✗	✗	✗	●	✓	Vigilant holons observe aggregate outcomes across holons to detect emergent or structural bias at higher hierarchy levels
Decision transparency & traceability	●	●	✓	✓	●	Transparency artifacts produced by local holons are composed recursively to support explainability at higher abstraction levels
Conflict detection between holons	✗	✗	✗	✗	✓	Vigilant holons act as supervisory holons that detect inter-holon conflicts and trigger coordination or re-orchestration
Global situational awareness	✗	✗	●	✗	✓	Vigilant holons synthesize partial awareness from multiple understanding holons into a system-level view
Runtime misalignment detection	✗	✗	✗	✗	✓	Misalignment between goals, norms, or outcomes is detected by vigilant holons and propagated upward to superholons for resolution

✓ indicates the holon has primary responsibility for the sub-objective, ● indicates a supporting or enabling role, and ✗ indicates no direct responsibility. ETH indicates ethical holon, EFH indicates effective holon, USH indicates understanding holon, UBH indicates unbiased holon, and VIH indicates vigilant holon

relationships, showing tackled issues, overlaps, and dependencies among holons.

Moreover, due to the fact that the effectiveness of these dimensions depends on coordinated operation, an orchestrator is needed to manage them. Given the nature of holons, as described in Sect. 2.1, collaboration must occur within a hierarchy, with a superholon leveraging holons of these dimensions to resolve requests and achieve objectives in a cohesive and seamless manner [39, 40]. Furthermore, since a holonic system interacts with external stimuli from heterogeneous environment, coordination mechanisms must be capable of handling runtime variability and uncertainty [37]. To address this need, the following section introduces the federated interoperability holon, designed to orchestrate collaboration, synchronization, and adaptation across holons in complex and evolving environments [9].

5 Federated Interoperability in Holonic Systems

In complex, distributed environments composed of heterogeneous and autonomous components, interoperability is not merely a desirable feature but a fundamental

requirement. As defined in Sect. 2.1, holonic systems, by definition, are composed of semi-autonomous entities (holons) that must operate both independently and cooperatively to achieve global system objectives. These holons are often developed by different stakeholders, deployed in different domains (e.g., logistics, healthcare, manufacturing), and governed by distinct data models, communication protocols, and ontologies. Without interoperability, holons become isolated entities, unable to share information, coordinate behaviors, or align goals – ultimately undermining the emergent intelligence and adaptability that holonic systems aim to provide.

The need for interoperability becomes even more pronounced in large-scale systems such as smart cities or cross-organizational supply chains, where no central authority controls all participating subsystems. In such contexts, interoperability must be achieved in a federated manner, meaning that independent systems maintain their autonomy while being able to interoperate seamlessly through shared standards, dynamic ontology alignment, and adaptable communication protocols. This federated approach allows for scalable, extensible, and resilient architectures, where holons can be added, removed, or modified without disrupting the overall system integrity. The objective is to establish

an interoperability-aware holon that satisfies the federated approach conditions and can oversee the other holons.

Achieving such federated interoperability is essential for enabling real-time decision-making, dynamic reconfiguration, and holistic optimization. It supports key holonic capabilities such as understanding, vigilance, and ethical reasoning by ensuring that relevant contextual data and intentions can be communicated and interpreted across heterogeneous domains. Thus, federated interoperability is not only a technical enabler – it is a strategic foundation for realizing the vision of intelligent, adaptive, and trustworthy holonic systems.

5.1 Interoperability

Interoperability refers to the ability of multiple organizations or systems to interact and communicate. Its proper implementation needs to take into consideration multiple aspects such as barriers, concerns, and the approach to be used [7]. As shown in Fig. 2, barriers are incompatibilities obstructing communication or service use and are categorized as [58]:

- **Conceptual:** these involve semantic, syntactic, and semi-otic incompatibilities that may occur during information exchange.
- **Organizational:** these arise from disparities between software interfaces, communication protocols, or hardware components.
- **Technology:** these relate to incompatibilities found within organizational policies, structural frameworks, and management practices.

Meanwhile, these interoperability barriers span various organizational concerns including data, service, process, and business aspects [58]. Data concerns pertain to the exchange of data items and formats, while service concerns involve the ability to request, provide, and utilize service across

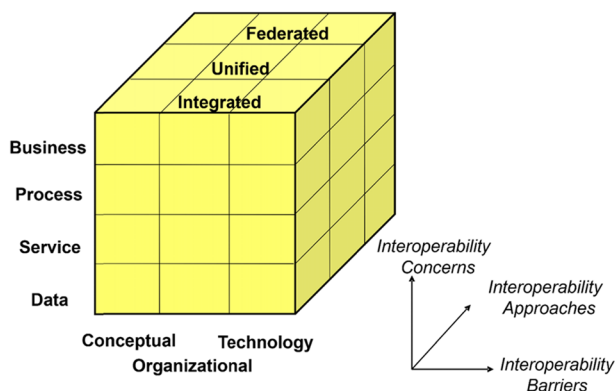


Fig. 2 Interoperability Framework INTEROP [7]

systems and organizations. Process concerns relate to the exchange of essential entities and information necessary for operations, and business concerns focus on collaboration in decision-making, commercial practices, and adherence to regulatory requirements at different organizational levels. Identifying these during planning ensures smooth cooperation and the proper implementation of the collaborative solution. Furthermore, such solutions are categorized into three approaches [58]:

- **Integrated:** all collaborating organizations adopt a single standardized format across their systems.
- **Unified:** a shared global representation layer, such as a common meta-model, is established to enable mapping between different systems.
- **Federated:** system model transformations between organizations are performed without any standardization or shared representation layer. It enables autonomous, heterogeneous systems or organizations to collaborate and interoperate without requiring full integration or centralized control, while maintaining their internal autonomy and structure.

5.2 Federated Interoperability

Federated interoperability is especially pertinent in systems-of-systems or multi-organization environments, where each participant must retain control over its internal processes while contributing to a collective operational goal. In such federated approaches, interoperability is negotiated at runtime – often facilitated by middleware, semantic adapters, or dedicated interoperability agents – rather than enforced through complete integration or uniform standardization. In their recent work, Daou et al. [8] emphasize the critical role of federated interoperability in enabling AI-driven, simulation-supported collaboration across enterprise models. They argue that interoperability must be dynamic, context-aware, and resilient, particularly within evolving digital ecosystems like smart cities or adaptive supply chains.

In the context of federated interoperability, the term *on-the-fly* denotes a system's ability to perform tasks dynamically at runtime, as opposed to relying on pre-defined, static configurations established during design. For holonic systems, on-the-fly capabilities are essential for real-time adaptation, contextual integration, and situational responsiveness. Specifically, on-the-fly interoperability enables holons – autonomous and heterogeneous components – to establish semantic, functional, and procedural links as needed, without requiring prior agreements or exhaustive central coordination. This means that when a new holon joins the system, it can dynamically discover, interpret, and communicate with other holons. This is achieved by generating or aligning short-lived ontologies

– temporary, purpose-driven semantic models created or adapted at runtime to support interoperability [25] – mapping data schemas, and negotiating operational interfaces during runtime. This concept fosters scalability and agility, especially in environments with frequent configuration changes such as smart cities, supply chains, or cyber-physical systems. For instance, when an unexpected event occurs (e.g., a traffic incident or supply chain disruption), federated interoperability holons must reconfigure the system on the fly by coordinating new behaviors, reallocating resources, and integrating additional data sources – all without restarting the system or requiring manual reprogramming. Thus, *on-the-fly* embodies runtime adaptability, enabling holonic systems to be self-organized, resilient, and context-aware. It represents a foundational capability for achieving federated, real-time interoperability in distributed intelligent systems.

Federated interoperability is particularly vital for holonic systems operating in distributed environments. It ensures that holons can communicate and collaborate across heterogeneous systems, organizations, and platforms – an essential requirement in large-scale systems such as smart cities, where multiple stakeholders and technologies must work seamlessly together.

For example, within a smart city or territorial ecosystem, federated interoperability could allow holons from transportation, energy, and healthcare systems to share data and coordinate actions, thereby enhancing overall efficiency and resilience across the territory.

Achieving federated interoperability requires addressing technical challenges such as data integration, standardization, and security. Solutions involve developing standardized communication protocols, ensuring data privacy, and implementing robust security mechanisms.

Recent research by Daou et al. [8] explores enabling federated interoperability in enterprise models through artificial intelligence and simulation. Their work highlights the importance of integrating AI and simulation techniques to facilitate seamless interoperability across diverse enterprise models. By leveraging AI, they propose a framework that supports dynamic adaptation and real-time decision-making – crucial capabilities for managing complex and distributed systems.

The framework proposed by Daou et al. [8] comprises several key components:

- **AI-Driven Interoperability:** Utilizing AI algorithms to facilitate communication and data exchange between heterogeneous systems, enabling holons to comprehend and process information from diverse sources for effective collaboration.
- **Simulation-Based Validation:** Employing simulation techniques to validate the interoperability framework,

demonstrating how it adapts to changing scenarios and maintains seamless interoperability.

- **Dynamic Adaptation:** Incorporating mechanisms that allow the framework to adjust in response to new requirements and constraints, a vital feature for sustaining interoperability in dynamic and evolving environments.

These findings provide valuable insights into the practical implementation of federated interoperability within holonic systems. They underscore the necessity of a holistic approach that combines AI, simulation, and dynamic adaptation to achieve effective interoperability.

Beyond technical considerations, developing standardized protocols and data formats is fundamental to ensuring compatibility and facilitating communication between systems. Moreover, fostering cooperation among industry, academia, and government is critical to the successful deployment of federated interoperability.

By integrating these recent advancements, holonic systems can attain a higher degree of interoperability, enabling more efficient and effective operation in distributed environments. This capability is particularly crucial for applications in smart cities, where diverse systems and stakeholders must collaborate to achieve shared objectives.

5.3 Federated Interoperability Holons: Connecting the Holons Together

In highly dynamic environments where heterogeneous holons operate and interact in real time, maintaining full semantic interoperability can be a complex and computationally expensive task. Integrated and unified interoperability approaches require either a single common model or a shared representation layer, which imposes strong global constraints on all participating entities and limits their ability to evolve independently [52]. Such constraints are particularly problematic in holonic systems, where holons are characterized by local autonomy, internal heterogeneity, and recursive organization across multiple levels.

By contrast, federated interoperability does not require a single shared meta-level model or a fixed standard applied across all participants. Instead, it enables runtime mediation and contextual semantic alignment between heterogeneous systems, allowing each holon to preserve its internal representations, decision logic, and operational scope while still achieving effective coordination [52]. This approach respects the principle of holonic autonomy and supports cooperation across hierarchical levels and organizational boundaries without requiring every participating entity to adopt the same fixed structure. Research in multi-agent and autonomous system domains has previously highlighted the importance of semantic interoperability – ensuring that meaning is consistently interpreted across heterogeneous components

– for coordinated behavior and collective decision-making [51].

Furthermore, since holons may dynamically assume different roles depending on context and may interact with external systems governed by distinct domain logics and vocabularies, federated interoperability provides the flexibility needed to manage changing situations without requiring global reconfiguration or centralized control. Therefore, based on these constraints and the principles of federated interoperability, we propose the Federated Interoperability Holon (FIH). Setting up FIH ensures that the various types of holons, defined in Sect. 4, can seamlessly communicate and collaborate within a larger system. These holons can act as the connectors that dynamically bind the holonic system together, enabling the exchange of information, coordination of actions, and alignment of goals across different subsystems and domains.

This federated interoperability holon coordinates all the other holons into working as a whole to satisfy a proposed objective. The efficient and effective holons can be joined in the form of multiple components in terms of either validation layers or used in the form of subsystems to balance cost and performance. However, given that their objective does not extend further, it needs a guide on when to act to be synchronized with the rest of the subholons present within the FIH. Hence, a hierarchical nature presents itself within the system.

This system, which is mostly oriented toward collaborations or even generic systems in enterprises, needs access to data, services, and processes found within organizations. Hence, to facilitate communication, increase accuracy and lower resource usage when engaging in search and retrieval, unbiased holons are needed. These holons can either check for a bias rate in writing or storage components, or even be themselves storage for a form of dictionary that is used to facilitate searches or information retrieval and dispatch while not losing accuracy due to bias.

The superholon also requires that some of its components be monitored to make sure that their resulting outputs are ethical and do not go against certain rules and morales. It could be a validation layer that checks for these characteristics (safety, morality...) in certain workflows as defined by the system or even components that are used to secure certain sent information such that no sensitive information is leaked.

All these special types of subholons as well as other supporting or artificial intelligence based holons need to be monitored by autonomous holons capable of rationalization and decision making. Hence, orchestrators are needed, and these can also be called vigilant holons given their definitions.

Additionally, FIH also needs to facilitate communication between heterogeneous holons and collaborating elements.

In dynamic, distributed, and rapidly evolving environments, particularly within holonic architectures, short-lived ontologies offer a lightweight and adaptable approach to semantic interoperability. Unlike comprehensive domain ontologies that aim for completeness and long-term stability, short-lived ontologies are designed for specific, often time-bounded interactions – such as a task phase, simulation episode, or service exchange. They are created, used, and discarded or updated as necessary, enabling systems to maintain semantic coherence without the overhead of maintaining large-scale ontology repositories [25]. This is especially relevant for federated holonic systems, where autonomous components – each with domain-specific logic – must interact on the fly. Short-lived ontologies act as temporary semantic contracts, enabling different types of holons (ethical, vigilant, understanding, etc.) to share situational understanding, align goals, and resolve semantic mismatches in real time, as discussed in ontology versioning approaches for the Semantic Web. These approaches explicitly manage ontology evolution by tracking changes across version, supporting the coexistence of multiple ontology states, and defining mappings or transformation rules between successive versions to preserve semantic interoperability [25]. The ontologies are instantiated at runtime, used for local decision-making or negotiation, and discarded or updated when no longer relevant [65]. Short-lived ontologies are ideal for Federated Interoperability Holons, which must operate in real-time and adapt to evolving system states. For instance, in smart cities or healthcare systems, holons can use temporary ontologies to interpret environmental conditions, negotiate emergency priorities, and exchange task-specific knowledge with new or unknown partners. This dynamic capability is supported by ontology matching and runtime semantic translation, which allows systems to function even when complete semantic alignment is not feasible beforehand.

5.3.1 Key Functions of Federated Interoperability Holons

Federated interoperability holons are pivotal in enabling semantic and functional coordination between holons operating across diverse platforms. One of their fundamental responsibilities is communication facilitation. By serving as translators or brokers, they abstract differences in syntax, schema, and ontology with standardized protocols and lightweight ontology alignment mechanisms [10]. This ensures robust and scalable data exchange even in heterogeneous environments.

These holons also enable goal alignment in systems where multiple autonomous agents may operate with partially overlapping or even conflicting objectives. Federated interoperability holons mediate these differences through adaptive coordination mechanisms that promote convergence toward shared system goals. For example, ethical holons focused

on safety may need to be coordinated with effective holons prioritizing efficiency – necessitating higher-level negotiation orchestrated by the interoperability holon.

Data integration is another essential function. Federated interoperability holons aggregate real-time, historical, and external datasets, ensuring that each holon involved in decision-making has timely access to accurate information. This capability is consistent with data integration strategies seen in semantic sensor networks and distributed digital twins [29].

Conflict resolution is supported by predefined rules or AI-enhanced adaptive strategies, where federated interoperability holons arbitrate among holons based on contextual constraints and prioritization schemes. Finally, dynamic adaptation is enabled through real-time monitoring and flexible reconfiguration of holonic roles, services, and workflows – an essential feature in dynamic systems such as cyber-physical infrastructures or autonomous logistics [30, 32].

5.3.2 Implementation, Contexts and Illustrative Examples

The value of federated interoperability holons can be illustrated through the deployment of interoperability platforms in smart environments. In smart cities, such systems can enable coordination among transportation, energy, and healthcare domains. Given the current rigid state of these platforms, their transition to federated interoperability holons would bring about more autonomous and flexible behavior. During an emergency, for instance, and in the case that FIH are properly developed, they can ensure that transportation platforms prioritize emergency vehicles – aligned with ethical holons – energy systems redirect power to critical infrastructure – aligned with effective holons – and healthcare systems prepare based on incoming demand forecasts – aligned with understanding holons.

In global supply chains, federated interoperability holons can facilitate seamless data and decision flows among geographically and functionally distributed stakeholders. For example, when facing disruptions due to geopolitical or climatic events, these holons can enable rerouting by soliciting vigilant holons, while maintaining ethical labor practices across vendors through ethical holons – consistent with the dynamic coordination proposed in federated simulation models [66].

Given the expected benefits brought by the FIH, there needs to be robust underlying systems supporting this concept. A potential FIH architecture is comprised of 6 main components:

- **Orchestrator:** This component manages the underlying elements of the system and possesses autonomous decision-making capabilities. These capabilities enable

the orchestrator to fulfill the principles of federated interoperability, which require operations to be carried out automatically without prior knowledge of the interacting systems. Consequently, the component can efficiently utilize the tools and elements at its disposal to produce satisfactory results. Furthermore, since the FIH is a holon within a holonic system, the orchestrator acts as a super-holon relative to the underlying elements of the FIH. To fully leverage its characteristics, an appropriate underlying system is required – such as a large language model [6, 24], one of the most recent and successful types of AI models. LLMs possess the ability to make rational decisions based on given inputs and to employ available tools to deliver satisfactory outcomes. Therefore, it stands to reason that this component would take the form of an LLM.

- **Integrator:** This component discovers and adds the metadata of any new component, tool, holon or collaborating element – service, database, process – as a node to a graph, Element Capability Graph (ECG), that contains all possible links between existing aforementioned elements based on various constraints such as input/output specifications and functionalities. This graph is used to keep a record of elements involved in the system and to facilitate workflow generation.
- **Translator:** This component manages translation between various inputs and outputs on a semantic and syntactic level. At the implementation level, this component could also take the form of an LLM. However, while its reasoning ability makes it a strong candidate for serving as the orchestrator's underlying system, it is the LLM's capacity to perform translations effectively and adapt to new types of inputs and outputs as situations evolve that makes it well-suited to power the translator [6, 24].
- **Element Finder:** This component searches the ECG of the system and finds the corresponding element based on a request from one of the users or associated systems of the FIH.
- **Workflow Generator:** This component creates a blueprint of a workflow that links the requestor – user or associated system – with intermediate tools and the receiver based on the request.
- **Workflow Executor:** This component links the elements identified by the Workflow Generator and executes the workflow.

These components ensure the proper execution of FIH characteristics and benefits given their underlying holonic, flexible, and automated nature. However, depending on the degree of autonomy that stakeholders and developers want their system to exhibit, the last two components – the workflow generator and the workflow executor – may be excluded. In that case, FIH cannot influence the connectivity

between holons and tools and is limited to controlling the system's execution.

5.3.3 Technical and Organizational Challenges

Despite their potential, several challenges hinder the full deployment of federated interoperability holons. Standardization remains a major obstacle. Developing communication protocols, data schemas, and ontologies that are broadly applicable and accepted across industries is a non-trivial task requiring interdisciplinary consensus and governance structures [10].

The issue of scalability also arises, particularly as the number of holons and their interactions increases. Without careful architectural planning, the semantic reasoning and coordination load may result in unacceptable latencies or resource bottlenecks [13].

Moreover, security and privacy are critical concerns. As federated interoperability holons often mediate sensitive exchanges (e.g., patient records or logistics contracts), they must implement robust cryptographic, access control, and auditing mechanisms to prevent breaches and ensure compliance with data protection regulations.

Addressing these multifaceted challenges necessitates an integrative exploration of advanced technological directions. The integration of AI-based conflict anticipation and decision optimization could enhance the autonomy and resilience of federated interoperability holons. For example, holonic energy management systems where each holon includes a prediction agent allow for anticipating shifts in demand and supply, potentially preempting service degradation [57]. Likewise, blockchain technologies offer a complementary avenue for ensuring data integrity and accountability. The immutable recording of holon transactions can underpin trust, transparency, and traceability within decentralized and multi-stakeholder ecosystems [50].

Finally, sustained cross-domain collaboration is essential to define shared ontological patterns, interoperability protocols, and reference implementations. The formalization of such collaborative standards is instrumental in enabling holonic architectures to interoperate seamlessly across heterogeneous domains – including healthcare, energy, and smart manufacturing – thus advancing both the theoretical and practical maturity of holonic interoperability.

5.4 Architectural Positioning and Interoperability Scope

Our proposed Federated Interoperability Holon is explicitly aligned with established interoperability barriers and concerns as defined in interoperability frameworks such as INTEROP [7]. In particular, this work primarily addresses

conceptual and organizational interoperability barriers, while enabling – but not directly enforcing – technical interoperability.

At the conceptual level, holonic systems are characterized by semantic heterogeneity, as holons may rely on distinct ontologies, vocabularies, and domain assumptions. This work addresses semantic and syntactic mismatches through runtime mediation mechanisms supported by short-lived ontologies and dynamic semantic alignment. Rather than imposing a global shared ontology, the FIH enables contextual interpretation and meaning negotiation on demand, thereby reducing the rigidity and computational overhead typically associated with integrated or unified interoperability approaches.

At the organizational level, holons may be governed by different objectives, policies, and operational constraints, particularly in cross-domain or multi-stakeholder environments. The FIH supports organizational interoperability by coordinating goals, synchronizing actions, and mediating conflicts between holons with partially aligned or competing objectives. This coordination occurs without centralized control over internal holon logic, preserving local autonomy while enabling coherent system-wise behavior.

While technical interoperability – including communication protocols, data formats, and middleware – is a prerequisite for any interoperable system, it is treated in our work as an enabling layer rather than a core contribution. Our proposed architecture assumes the availability of suitable technical interfaces and focuses instead on higher-level semantic and organizational alignment, which remain major challenges in large-scale holonic and system-of-systems environments [12, 52].

In terms of interoperability concerns, the proposed approach primarily target:

- Data and service concerns: it enables semantic mediation and adaptive service discovery across heterogeneous holons.
- Process concerns: it supports dynamic workflow generation, orchestration, and reconfiguration at runtime.
- Business and decision concerns: it enables coordinated decision-making that respects ethical, unbiased, and contextual constraints across organizational boundaries.

By positioning federated interoperability as a system-level capability, our work clarifies that the FIH does not replace individual holons or enforce uniform behavior. Instead, it acts as a supra-holonic coordination mechanism that addresses interoperability barriers where they most critically impact holonic systems: at the intersection of semantics, organization, and dynamic adaptation.

6 Federated Interoperability for Rural Mobility Case Study

To demonstrate the practical application of the proposed framework, we present a detailed case study on federated interoperability in rural mobility. In this scenario, a holonic system architecture is proposed to improve transportation accessibility and efficiency in sparsely populated areas, where traditional public transport solutions are often inadequate.

6.1 Case Study Overview

Rural mobility remains a significant challenge due to limited infrastructure, low population density, and the high cost of maintaining regular public transport services. Traditional centralized mobility solutions fail to adapt to the dynamic and dispersed nature of rural transportation needs. Holonic systems offer a promising approach by enabling decentralized, adaptive, and interoperable solutions that leverage multiple mobility services and stakeholders. Other than synchronizing various modes of transport, this platform allows the localization of rural transit deserts, i.e. locations without means of transport in rural areas, especially public transportation. This is due to the fact that people living in those regions are more likely to rely on private transportation such as cars and bikes.

6.2 Case Study Functionalities

The case study involves the proposition of a holonic system architecture with the following functionalities:

- **Data Collection:** the architecture proposes a collection of real-time and historical data on rural mobility patterns, including travel demands, vehicle availability, and environmental conditions, through IoT devices, GPS tracking, and user input.
- **Holonic System:** the architecture follows holarchy principles with the previously proposed dimensions in Sects. 4 and 5 to optimize rural mobility while promoting their detailed benefits to rural mobility.
- **Real-Time Coordination:** the architecture supports interoperability among different heterogeneous mobility service providers to ensure seamless travel experiences for users.
- **Rural Mobility Desert Discovery:** through the data collection functionality and the various types of holons used, the architecture supports the localization of rural

mobility deserts through gaps in transportation routes that rely on public transport.

- **Optimization and Adaptation:** through the data collection functionality and the various types of holons used, the architecture proposes to utilize holonic intelligence to dynamically reallocate transport resources, optimize routes, decrease rural mobility deserts, and respond to real-time changes in demand.
- **Simulation Validation:** the architecture supports a holon-based simulation that represents various transportation entities as holons, alongside internal system holons, integrating multiple modes of transport such as shared mobility services, on-demand buses, and ride-sharing solutions to support system validation and result evaluation.

6.3 Mapping Holons

To address the challenges of rural mobility, we propose a holon-based distributed system. This ensures federated interoperability, real-time data exchange, and adaptive decision-making. The system builds directly on the Generic Holonic System framework introduced in Sects. 4 and 5. Figure 3 presents the proposed holon-based system's operations instantiated for the rural mobility scenario. The process begins with the initialization of the distributed system where the orchestrator, a role taken by the federated interoperability holon, sets up the federation and ensures synchronization among all participating holons – representing transport services, users, and infrastructure. At this stage, ethical and unbiased holons establish the initial transport allocation policies, embedding fairness and transparency into the system from the outset.

During the real-time data exchange and coordination phase, traveler holons – understanding holons responsible for the communication between the user and the platform – submit trip requests based on current needs, as shown in Fig. 4. Subsequently, transport service holons – unbiased and effective holons responsible for the analysis of the request and the current mobility situation – respond with dynamic routing and pricing strategies. Simultaneously, infrastructure holons – vigilant holons responsible for monitoring road conditions, congestion, and weather conditions – continuously provide updates, ensuring that all decisions are informed by the latest environmental data. These updates are transmitted through the communication holon, an unbiased holon that dynamically manages data exchanges between the system and the mobility organizations while translating incoming data. Furthermore, any metadata collected by these three holons about the collaborating organizations available services and dataset is stored within the communication holon in the form of an ECG which helps reduce the time required to identify which service or database is

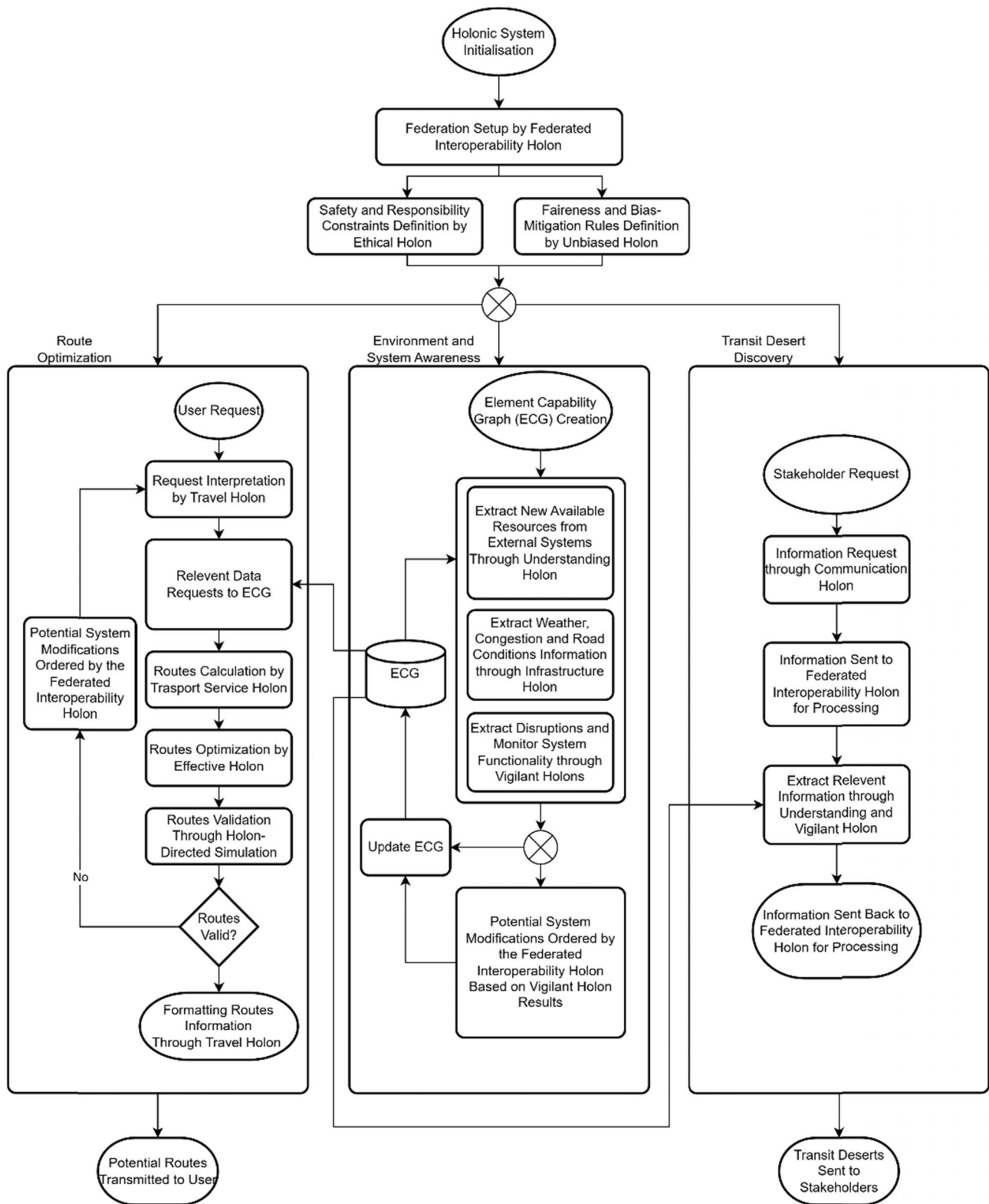
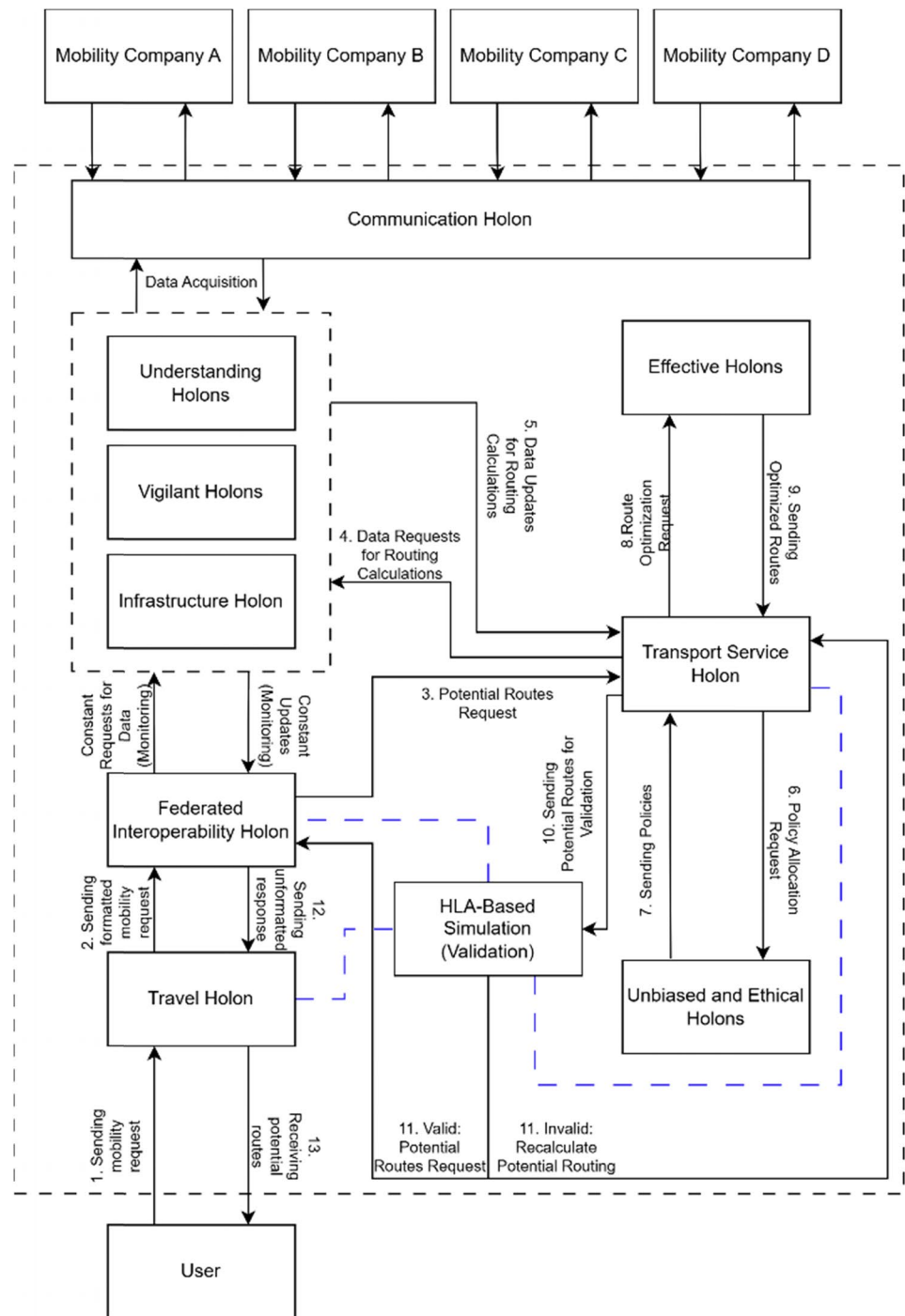


Fig. 3 Hologic System Operations for Rural Mobility. An ellipse represents the start of a chain of processes, a rectangle represents a process or a subprocess, rounded rectangles represent the end of a chain

of processes, and a circle with a cross mark represents a junction where all the output elements are executed

Fig. 4 Holonic System for Rural Mobility. Numbered steps follow the procedure to obtain potential routes from one destination to another while unnumbered steps are continuous and always take place for the sake of monitoring and acquisition of data relevant to transit deserts. This is controlled by the Federated Interoperability Holon which has the highest authority. Dashed blue lines denote components that are directly linked to the simulation component and used for system monitoring and validation



needed from the collaborators. Through the hierarchical structure of the holonic system, these components remain connected to the FIH and therefore align with the description provided in Sect. 5. The system then enters a phase of dynamic adaptation and optimization. Here, effective holons manage vehicle dispatching and load balancing to maximize efficiency, while understanding holons apply AI models to refine transport forecasts. Vigilant holons monitor disruptions such as delays or accidents and adjust mobility plans

in real time to maintain service continuity. Once the data is processed, potential routes are identified and optimized, and both the routes and the system's operation are validated with respect to performance and fidelity. The travel holon relays the information back to the user.

The execution of this holonic system is orchestrated by the federated interoperability holon that has autonomous decision making. It can also restructure workflows, holons, and tools according to the system's current needs,

encountered challenges, and warnings issued by the HLA-based holon-based simulation component – introduced in Sect. 6.4 – given its role as the superholon with the highest authority. In addition to the optimization of mobility for various users, this platform would allow companies to notice transit deserts where almost no mobility options are present. This second aspect would also allow them to better understand which areas need mobility improvements due to the vigilant holons monitoring the global situation as well as automated reports sent by understanding and effective holons about various zones that are avoided due to the lack of transportation options.

6.4 HLA Distributed Holon-Based Simulation

To operationalize, test the platform and provide validation about the architecture and its behavior, we adopt the High-Level Architecture (HLA) as the backbone of our

holon-based simulation framework. HLA provides a standardized infrastructure – known as the Runtime Infrastructure (RTI) – through which holons, replicated as HLA federates, can interact dynamically while preserving their autonomy. This modular design is particularly well-suited to the decentralized nature of rural mobility systems, where multiple actors and services must coordinate without relying on centralized control.

As seen in Fig. 5, this corresponds to the simulation block of the system. It replaces and emulates the calls of the users and test responses of the platform to different kinds of requests. The simulation begins with the initialization of the federation – by creating federate versions of the travel, transport service and federated interoperability holons – orchestrated by the Federate Federation Manager Holon – federate version of the federated interoperability holon with authority limited to the simulation while also acting as a subholon to FIH. This federate ensures that all participating entities

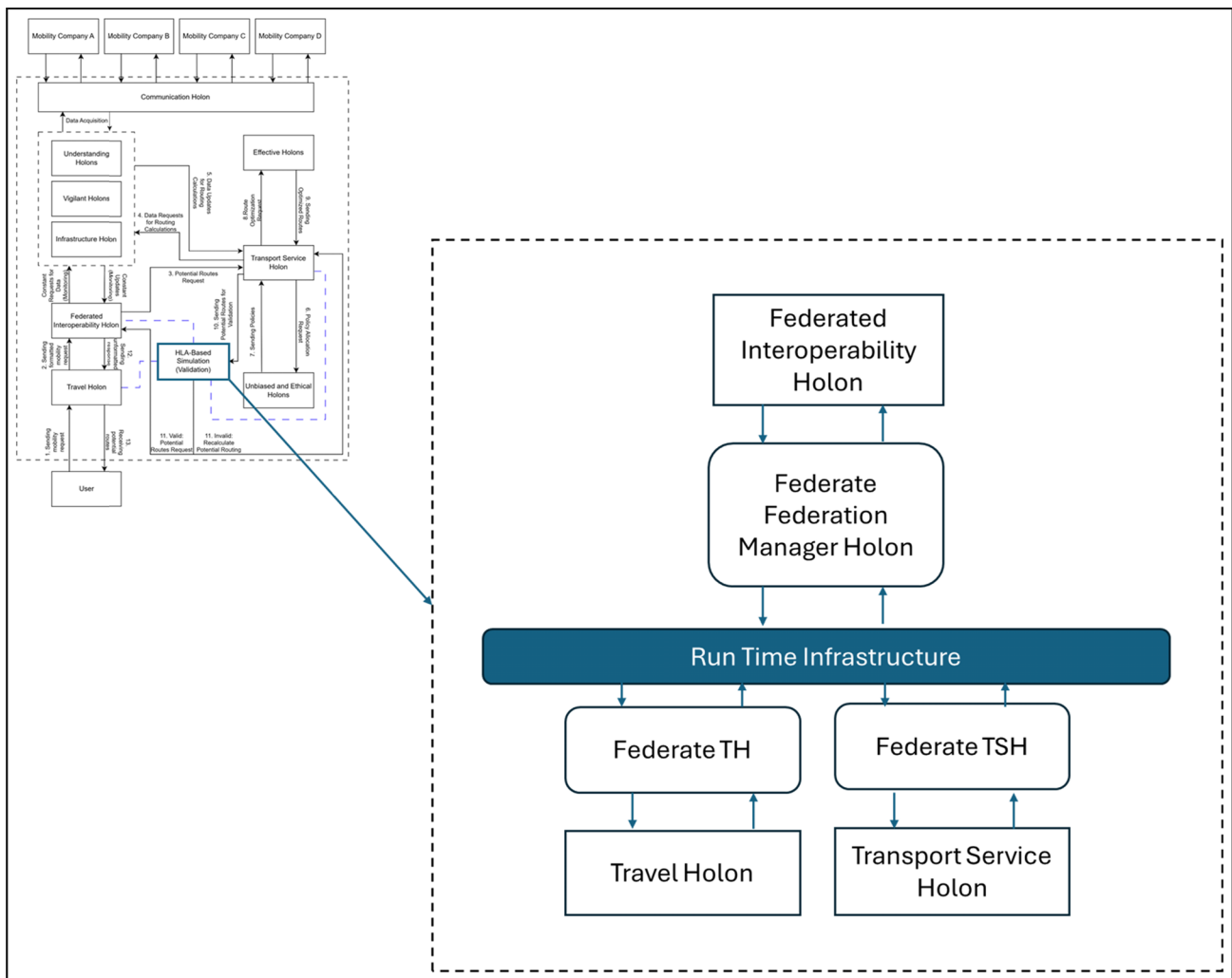


Fig. 5 HLA structure of the HLA simulation block

– ranging from transport services and infrastructure monitors to user-facing agents – are synchronized and aligned with the overarching goals of the simulation. In this simulation, the federates are connected to their corresponding holons to have access to the rest of the system and the data for testing and validation purposes. This means that this stage assumes the role of holon simulation mentioned in Sect. 3 since the holons themselves are the actors of the simulation.

Initially, ethical and unbiased holons play a critical role in retrieving transport allocation policies, embedding principles of fairness, transparency, and safety into the simulation's operational logic.

As the simulation progresses, holons – connected to the federates and the run time infrastructure (RTI) – engage in real-time coordination. Traveler federates submit mobility requests based on the simulated user needs through the RTI, while transport service federates respond with routing and pricing strategies tailored to current conditions obtained from its connections to the rest of the system through its holonic counterpart. Simultaneously, the federate federation manager holon accesses – through the federated interoperability holon and its connection to vigilant, understanding, and infrastructure holons – monitor environmental factors such as traffic, weather, and road accessibility, feeding this data into the rest of the simulation to inform decision-making.

Similar to the system's regular operations, the potential routes are refined and optimized before being sent back to the simulated user. If any errors, complications, or discrepancies arise – whether in comparison to normal system operations or to the previously obtained routes – the holon where the issue occurred flags it and reports it to the federate federation manager holon. It then invalidates the result and passes the information to its superholon.

In the final stages of the simulation, HLA time management ensures synchronization across all federates, enabling coherent execution and continuous learning. Holons update their strategies based on observed outcomes, contributing to a system that evolves and improves over time. These insights inform future iterations and guide real-world implementations. Furthermore, in both cases – when issues are detected during simulation and when execution proceeds without discrepancies – the simulation concludes with a performance analysis, evaluating key indicators such as travel time reduction, CO₂ emissions, and service accessibility. These metrics are subsequently applied to system updates and may trigger reinitialization in cases where potential routes are invalidated.

6.5 Discussion

This case study illustrates the transformative potential of holonic systems in addressing the challenges of rural

mobility. By harnessing the power of federated interoperability, holons facilitate efficient collaboration among diverse transport services, resulting in an adaptive, sustainable, and user-centric mobility network. One of the key strengths of this approach lies in its scalability. Thanks to their modular architecture, holonic systems can be easily expanded to incorporate new transport services and infrastructure, adapting seamlessly to evolving community needs.

Flexibility is another defining feature. The decentralized nature of holons allows for real-time responsiveness to shifting mobility demands, which is particularly valuable in rural areas where transportation needs are often dispersed and unpredictable. Interoperability, enabled through federated frameworks, ensures smooth coordination between service providers, eliminating fragmentation, and enhancing the overall coherence and efficiency of the transport ecosystem. Furthermore, its operationalization through a federated approach signifies that this system possesses autonomous decision-making abilities which signifies that it is a highly responsive and adaptive system.

Ethical considerations are embedded in the design of the system, with a strong emphasis on fairness, accessibility, and sustainability. By promoting equitable access to mobility services, the framework addresses the unique social and logistical challenges faced by rural populations. Furthermore, the environmental benefits are significant. By optimizing travel routes and reducing redundancy, holonic systems contribute to lower emissions and fuel consumption, aligning with broader goals for green and climate-conscious transportation.

Overall, this study proposes that holonic system, when combined with federated interoperability, has the potential to offer a viable approach for enhancing rural mobility. This framework could contribute to more inclusive, efficient, and environmentally responsible transport networks capable of adapting to the needs of diverse communities.

7 Conclusion

The concept of holons remains a powerful lens for understanding and modeling complex systems. By proposing a conceptual extension of the holonic system dimensions, this work seeks to advance the holonic paradigm and provide a foundation for addressing certain limitations of current autonomous and adaptive architectures, particularly in relation to ethical considerations, adaptability, and federated interoperability in complex and distributed environments.

In this context, we introduced a systematic conceptual organization of complementary holonic roles that conceptually integrates some aspects aimed at alleviating some of the concerns associated with intelligent and autonomous systems. Specifically, these roles are analytical

constructs that incorporate ethical reasoning, operational effectiveness, contextual understanding, bias awareness, vigilance, and federated interoperability within holonic system designs. Rather than imposing concrete implementations, they provide a holistic framework for examining how such concerns may be addressed within a coherent holonic perspective.

Building on this foundation, our work positions holon-directed simulation as a natural extension of the proposed framework. In contrast to classical agent-based approaches, holons-directed simulation emphasizes the dual role of holons as both simulated entities and autonomous actors capable of directing, monitoring, and adapting the simulation process itself. This perspective highlights simulation not merely as a modeling technique, but as an analytical and exploratory mechanism for studying coordination, emergent behavior, and trade-offs in federated and dynamic holonic systems.

The applicability of this approach was illustrated through a rural mobility use case, where holonic roles and federated interoperability mechanisms were instantiated within an operable distributed system, for user interaction, as well as an HLA-based simulation environment, for analytical and validation purposes. While this use case is not intended as a validation study, it demonstrates the applicability of the proposed concepts and their potential to support reasoning about resilience, fairness, adaptability, and federated interoperability in real-world settings.

Given the proposed concepts, we plan to further develop the methodological foundations of holon-directed simulation, including clearer characterization of holonic hierarchies, systematic evaluation strategies, and the role of simulation in supporting learning and adaptation over time. Additional research directions include developing shared ontologies for ethical and unbiased holons, as well as enhancing federated interoperability mechanisms. Moreover, due to the study's limitations – namely, the diverse transdisciplinary nature of the various holons and the current lack of empirical validation – we intend to apply the proposed concepts and architecture concretely to the rural mobility domain, as well as to broader fields of application, such as smart territories, enterprise ecosystems, and cyber-physical systems.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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